PXIE LEBT Solenoid

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For the PXIE LEBT should be built four water cooled solenoids combined with vertical and horizontal dipole correctors. Solenoid aberrations were investigated in [1]. The solenoid specifications [2] are shown in the Table 1.

Table 1

Parameter	Value	Units	Comments
Minimum inner diameter	80	mm	Required for 3” O.D. beam pipe with clearance; ‘*a*’ on Figure 1
Maximum outer diameter	400	mm	‘*b*’ on Figure 1
Maximum physical length	140	mm	‘*c*’ on Figure 1
Solenoid strength, $\int B^2 dz$	0.03	$T^2 \cdot m$	At peak current
Peak solenoid current	≤ 300	A	
Power dissipation	≤ 5	kW	
Dipole corrector coils	4		One pair for X and one pair for Y
Peak dipole coil current	≤ 10	A	
Dipole coil field integral	0.5	mT-m	At peak current
Integrated dipole field homogeneity	≤ 5	%	At radius ≤ 5 mm
Nominal input water temperature	32	ºC	
Water pressure drop	<70	psid	
Max water temperature rise	20	ºC	
Water connections diameter	≥ 0.25	in	
Water passage diameter	≥ 0.25	in	Preferable if other constraints permit
Alignment features	6		Fixtures will be provided by Fermilab; vendor is responsible for their installation - welded to yoke at mutually agreed locations
Solenoid finish	NAL blue		Finish coat over appropriate primer

The solenoid magnetic design was performed initially using OPERA2d axial symmetry code, and later by OPERA3d (TOSCA) code when solenoid was combined with dipole correctors (See Fig. 1). The solenoid consists of six pancake type coils surrounded by a low carbon steel yoke (AISI 1006 or AISI 1008). The copper conductor dimensions were chosen to limit: the current to 300 A, outer diameter to 400 mm, reduce as much a possible power losses, and cooling water heating.

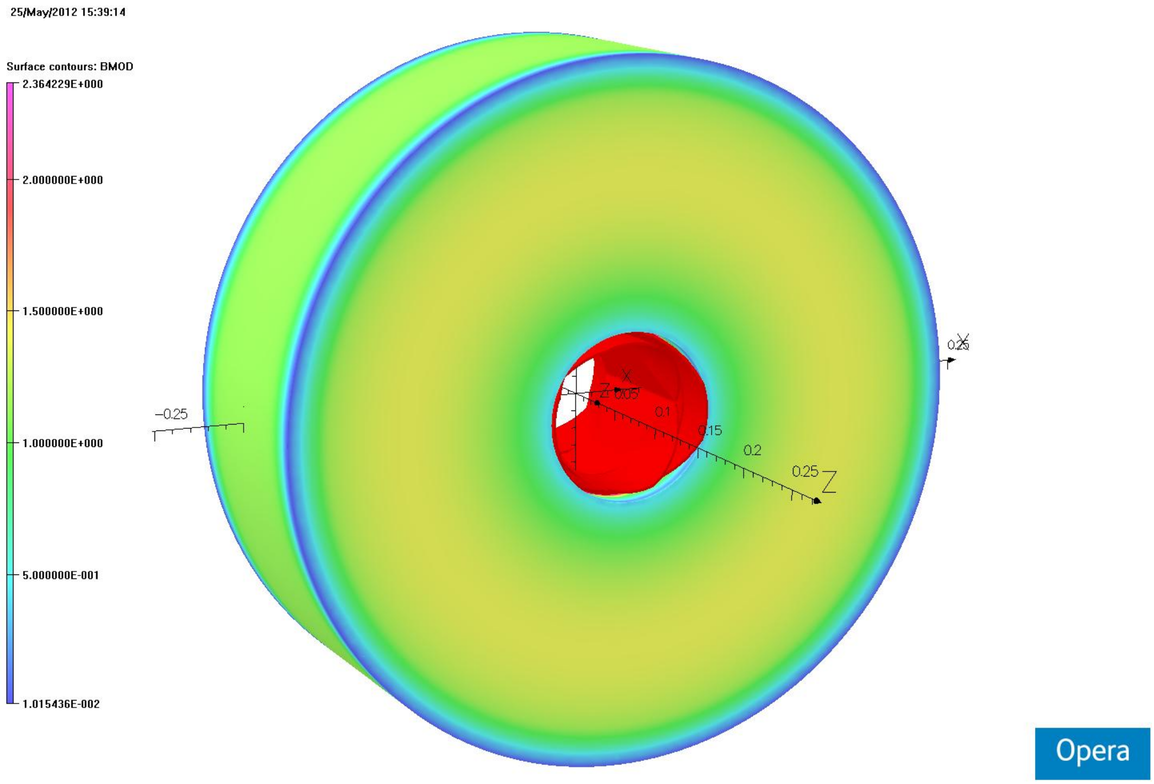


Fig. 1. Solenoid model geometry and flux density.

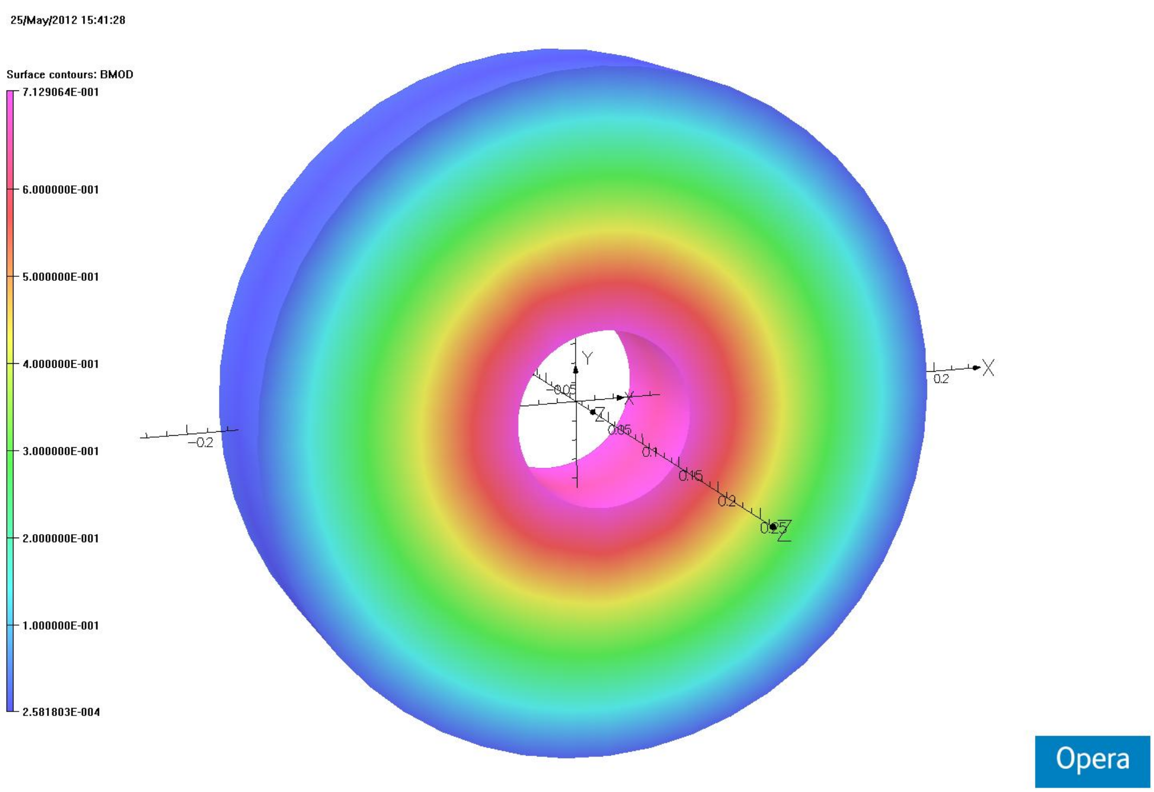
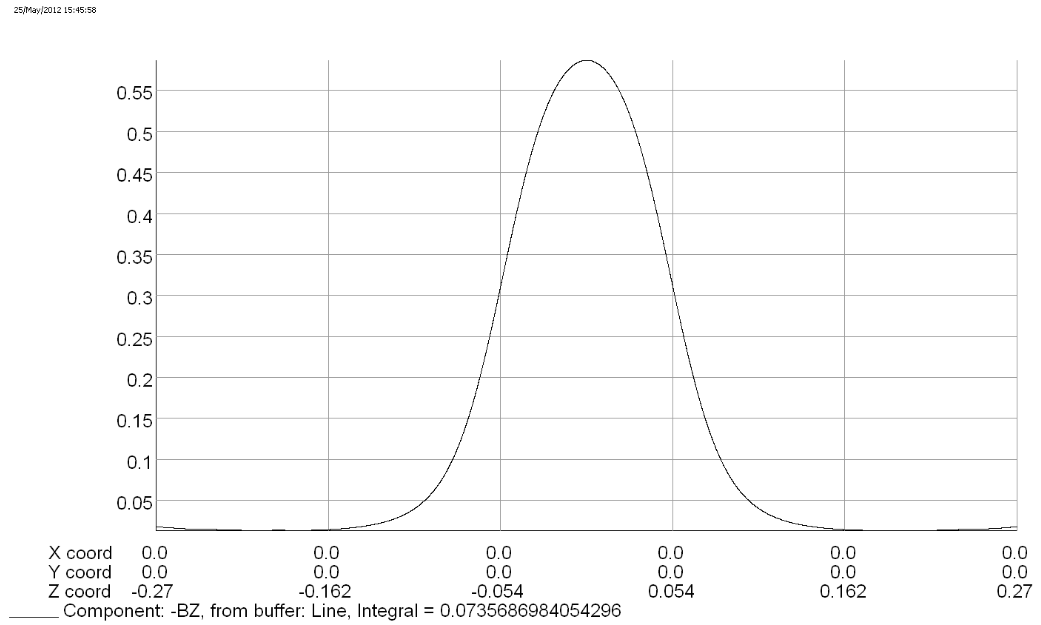


Fig. 2. Solenoid main coil and flux density.



Opera

Fig. 3. The Bz field component distribution along Z-axis. Bmax=0.587 T at the total current 55.4 kA.

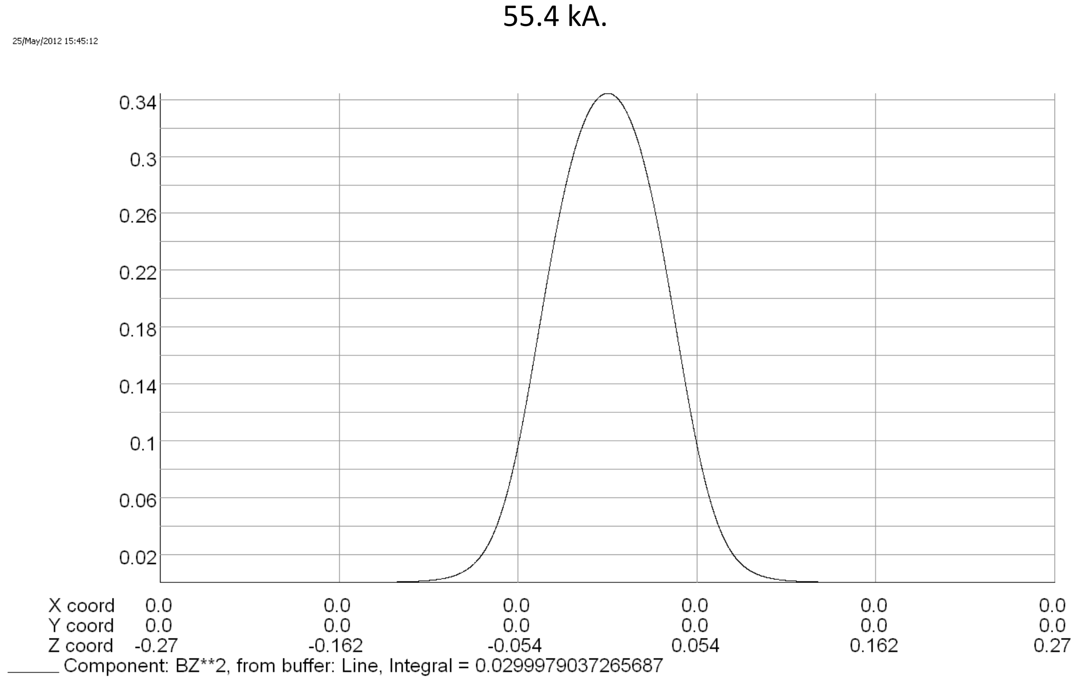


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Fig. 4. The integrated along Z-axis field of Bz^2 at 55.4 kA in the main coil.
The integral is 0.03 T^2-m as specified in Table 1.

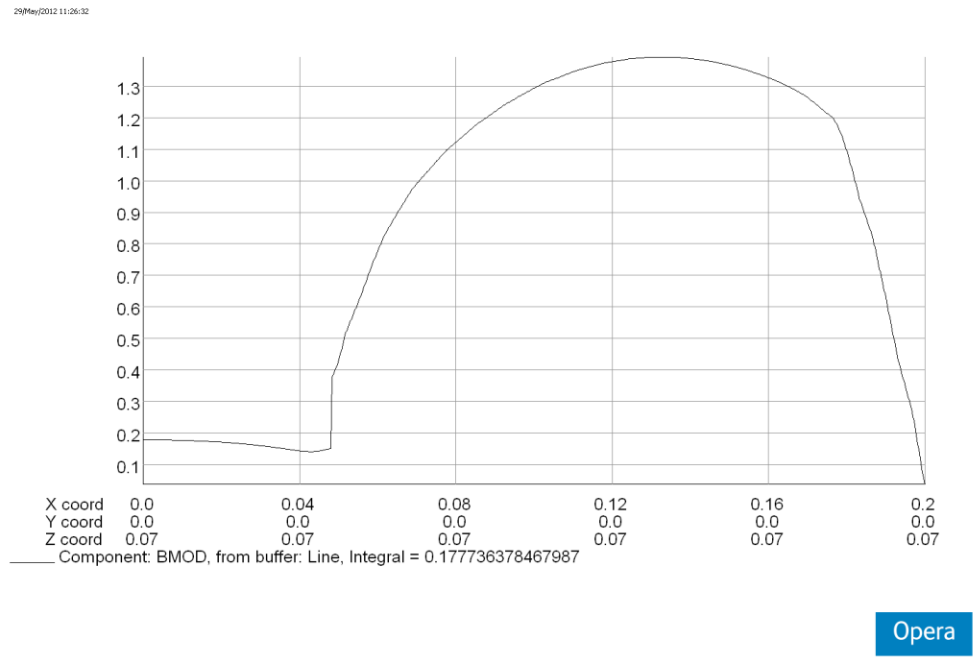

Fig. 5. The flux density in the solenoid iron end plates.

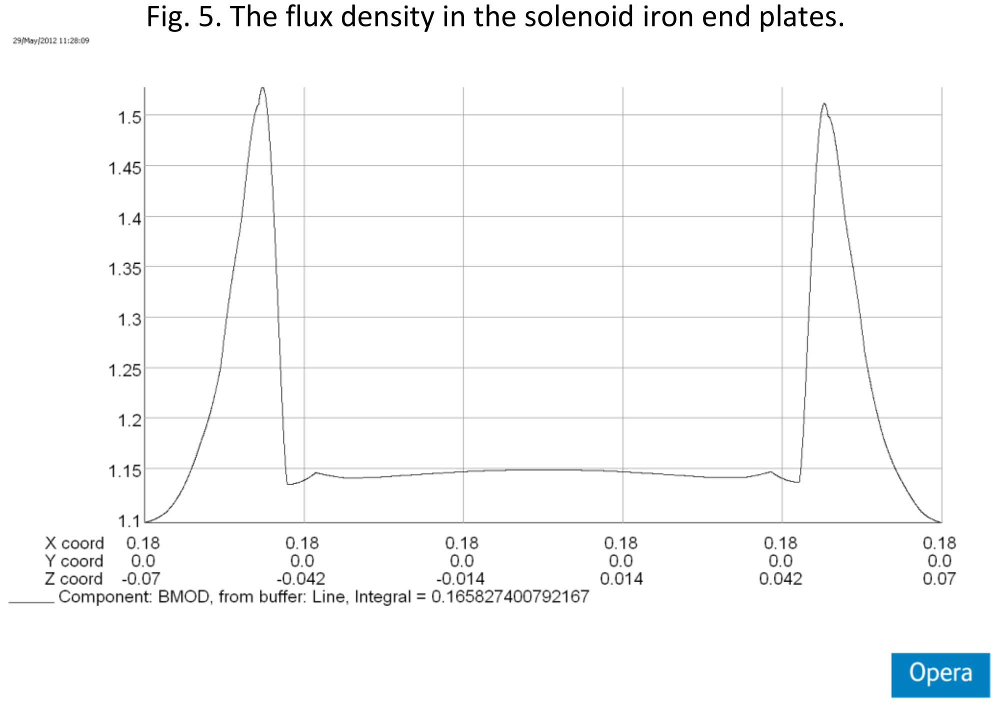

Fig. 6. The flux density in the solenoid outer iron cylinder.

The main solenoid coil combined with dipole correctors. There are several possible configurations of coils which could be used to form the dipole field: shell type coils or bedstead. The shell type coils increase the solenoid and yoke ID, the bedstead coils reduce the solenoid length. The shell type coil configuration was chosen to simplify fabrication and final magnet assembly. The results of total (solenoid+vertical and horizontal dipoles) magnetic field simulations are shown in Fig. 7 – Fig. 11.

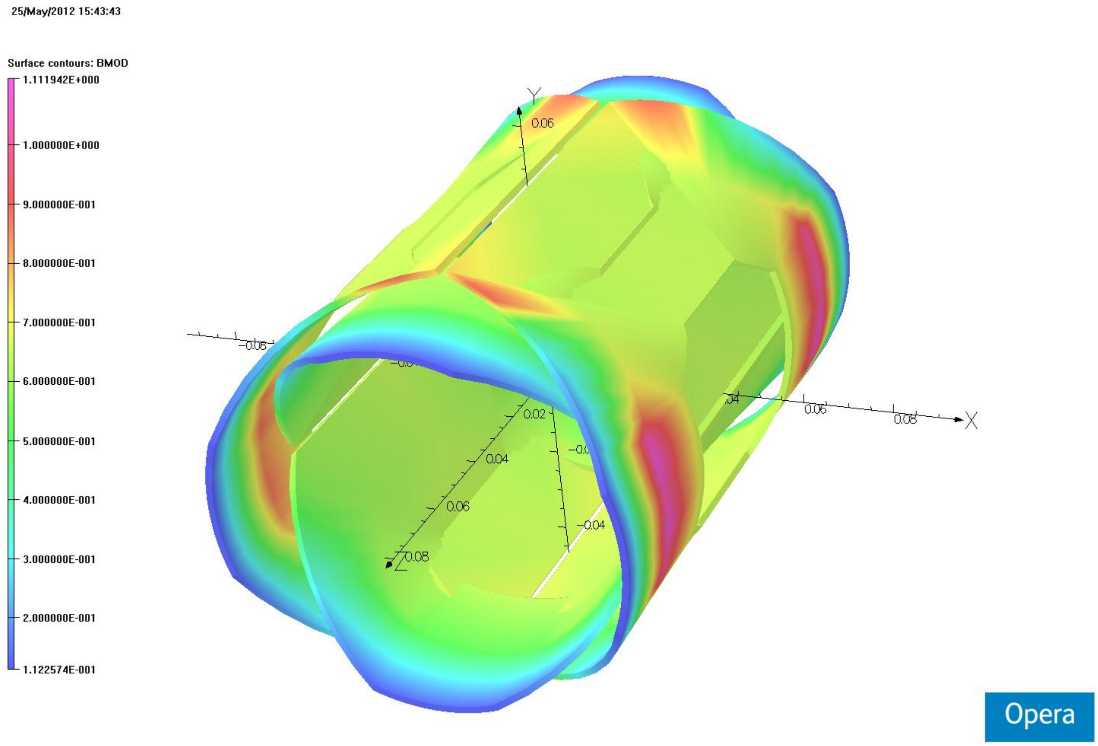

Fig. 7. Vertical and horizontal dipole correctors and flux density.

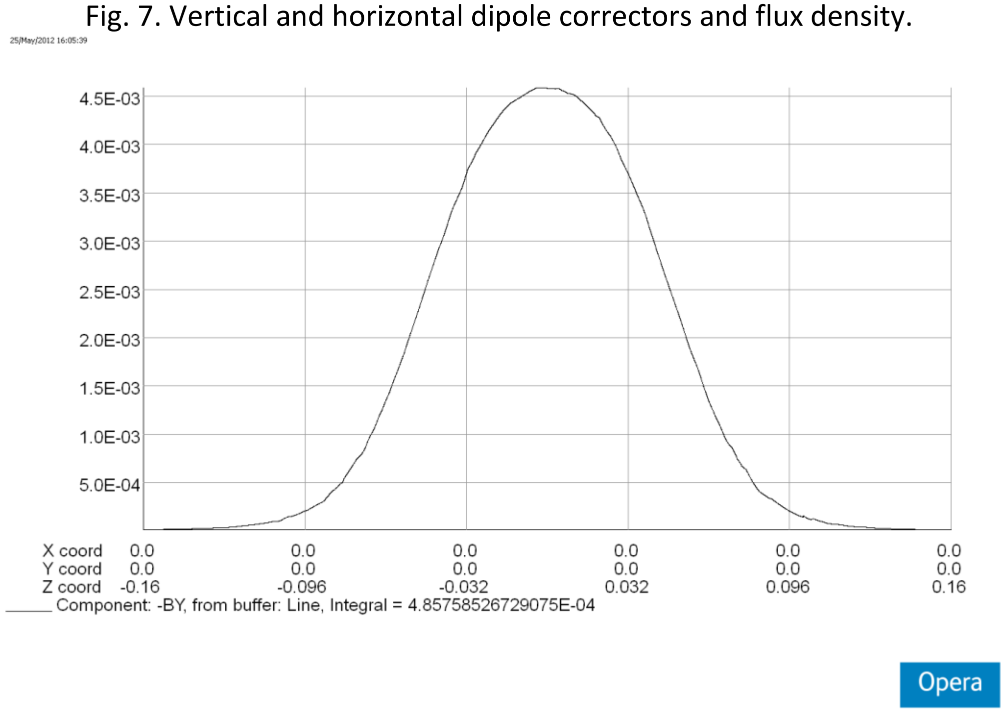

Fig. 8. Vertical dipole field distribution By at 235 A total coil current and 55.4 kA in the main coil. The integrated By field is 0.486 mT-m.

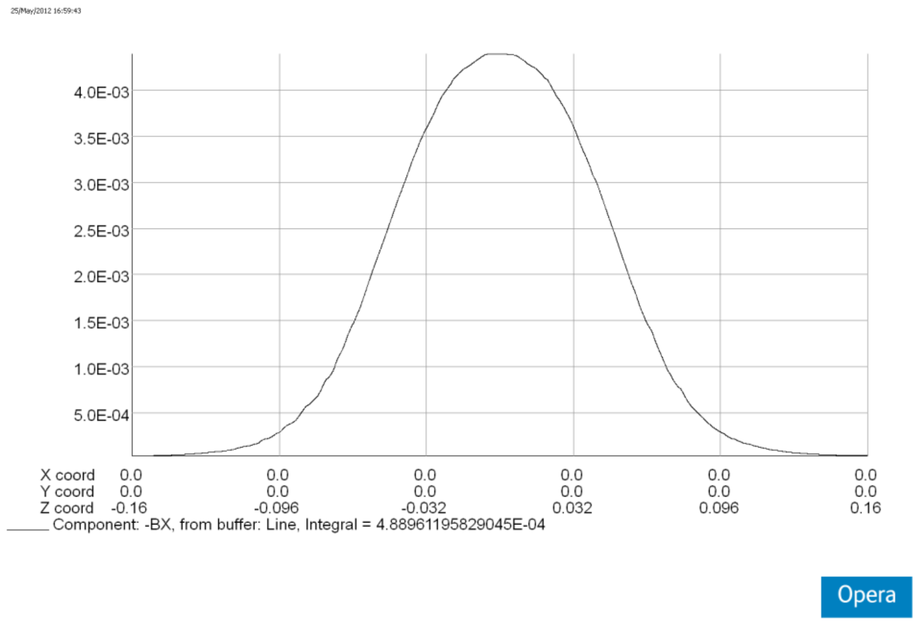

Fig. 9. Horizontal dipole field distribution Bx at 255 A total coil current and 55.4 kA in the main coil. The integrated By field is 0.489 mT-m.

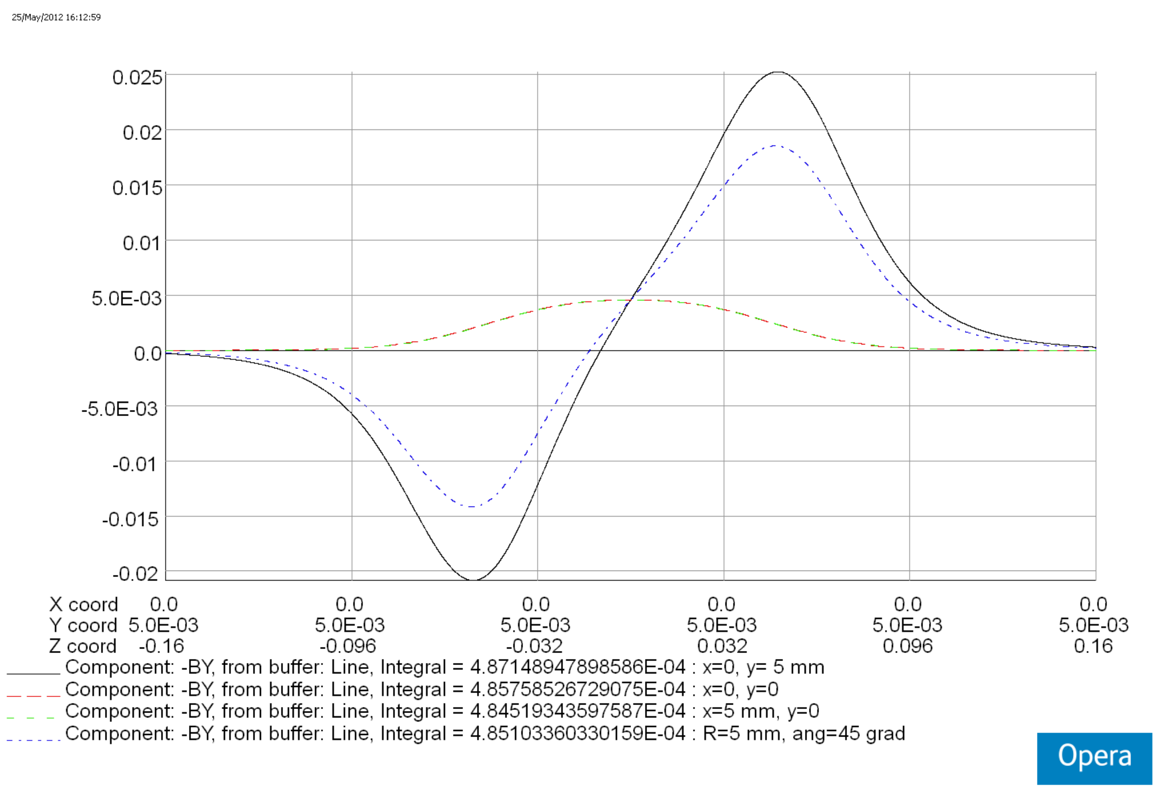

Fig. 10. Vertical field distribution-By for the solenoid center (x=y=0) and R= 5 mm. The integrated field homogeneity is 0.54 %.

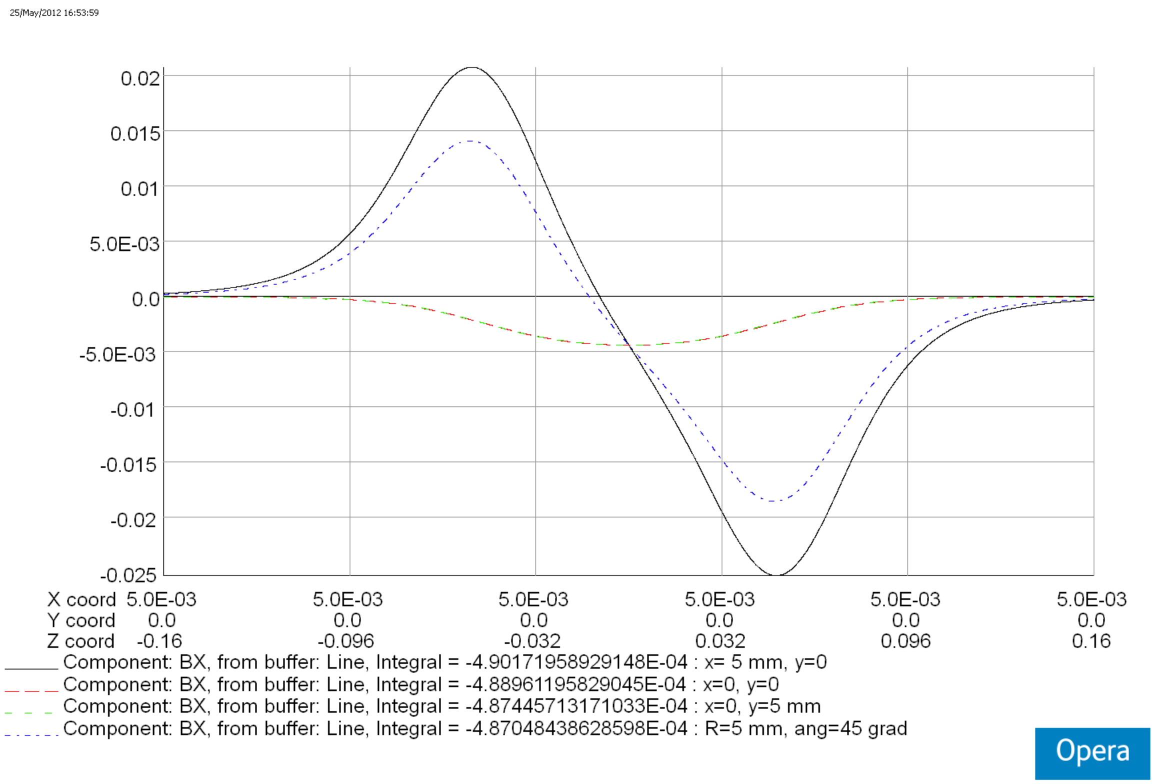

Fig. 11. Horizontal field distribution Bx for the solenoid center (x=y=0) and R= 5 mm. The integrated field homogeneity is 0.64 %.

So, the dipole corrector field homogeneity is better than specified 5 % shown in Table 1. The proposed solenoid parameters are shown in Table 2, and the solenoid geometry in Fig. 12.

Table 2

Parameter	**Unit**	**Value**
Solenoid peak field at 55.4 kA-turns	T	0.587
Integral $(Bz^2)dz$	T^2-m	0.03
Current	A	288
Number of turns		192
Number of pancakes		6
Coil resistance	Ω	0.08
Inductance	mH	12.2
Conductor	mm	6.5 x 6.5, dia. 3.0
Conductor length	m	133
Voltage	V	23
Power loss	kW	6.62
Water pressure drop	MPa	0.4

Number of water circuits		6
Water flow	l/min	4.2
Water temperature rise	°C	23

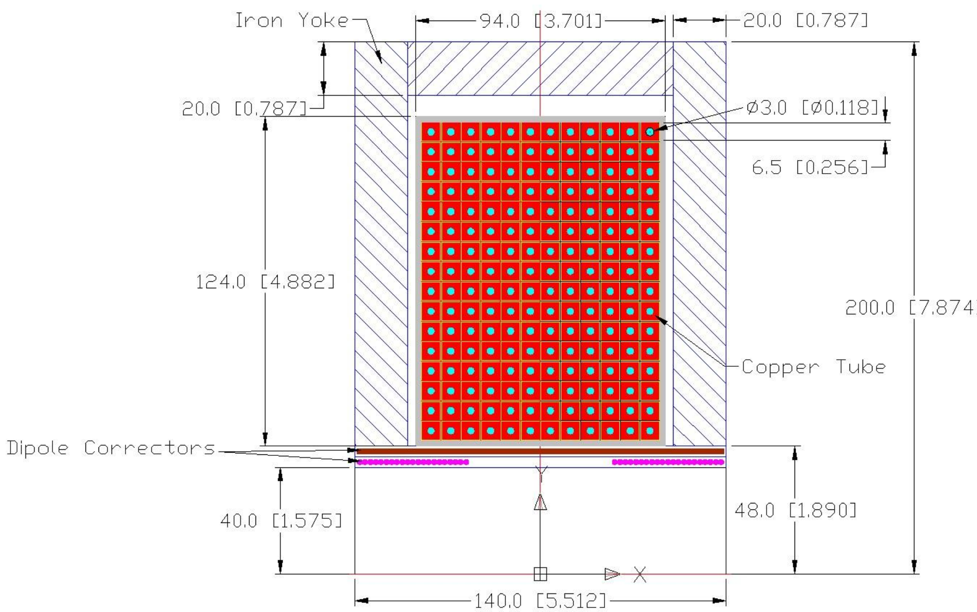

Fig. 12. Solenoid geometry. Dimensions are in mm [inch].

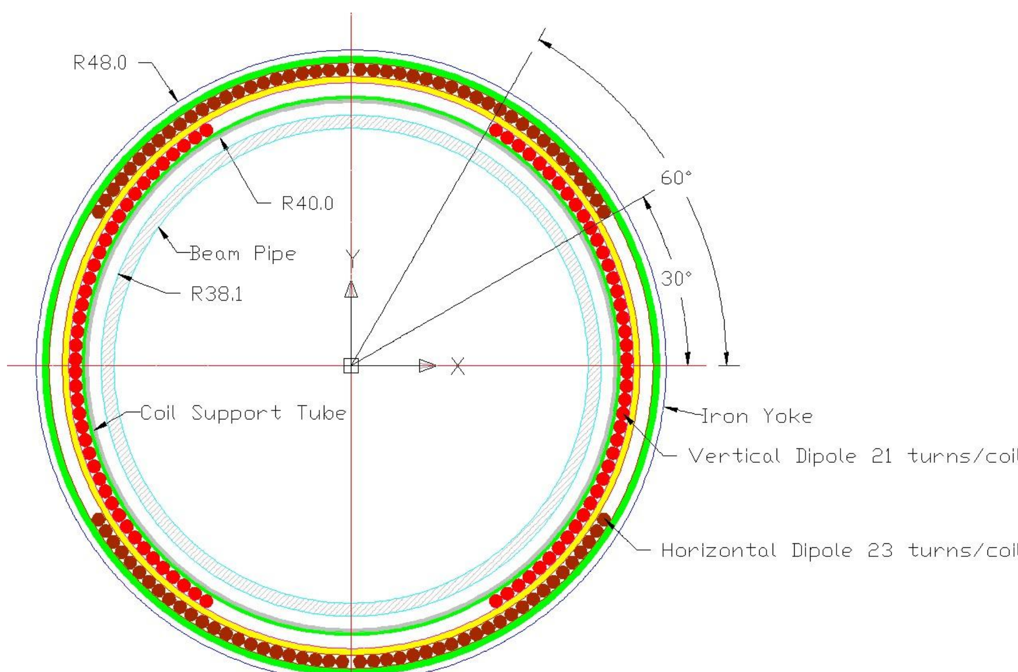

Fig. 13. Dipole corrector shell type coils cross-section. Dimensions are in mm.

The vertical dipole (VD) and the horizontal dipole (HD) corrector parameters are shown in Table 3, and the geometry in Fig. 13.

Table 3

Parameter	Unit	Value
Integrated dipole corrector field	mT-m	0.5
Dipole correctors assembly ID	mm	40
Dipole correctors assembly OD	mm	48
Peak current in the dipoles	A	11.5
Coil number of turns VD/HD		21/23
Number of coils VD/HD		2/2
Copper conductor diameter	mm	2.0
Current density	A/mm^2	3.7
Conductor length/magnet VD/HD	m	14/16
Resistance/magnet VD/HD	Ω	0.09/0.1
Voltage drop/magnet VD/HD	V	1.03/1.15
Power loss VD/HD	W	11.9/13.2

Summary

The described solenoid configuration with the ferromagnetic yoke is in an agreement with the main specified parameters. Nevertheless, the power losses 6.6 kW are larger of specified 5 kW value. The power losses could be reduced by increasing coil packing factor using conductor with larger relation Cu : Cooling hole areas. But in this case the current also should be increased to larger than specified 300 A value. The water temperature rise is 23°C (close to the specified 20°C) at 0.4 MPa pressure drop and 6 parallel water cooling circuits. The 8 mm total thickness of both dipole correction coils should be reduced to the minimum acceptable value during the final design study with corresponding decreasing of solenoid and yoke ID. The 20 mm thick yoke outer cylinder is chosen to compensate the influence of slots for the six pancake conductor outlets. Dipole coils should be glued to the inner solenoid bore to provide efficient indirect cooling from the main solenoid coil. The coil current and efficiency of correction coils could be increased by using rectangular copper conductor with dimensions 1 mm x 2 mm.

References

[1] L.R. Prost, A. Shemyakin, S. Nagaitsev, "Estimations of spherical aberrations for PXIE LEBT solenoids", Rev. B, 2012.

[2] LEBT solenoids specifications, http://projectx-docdb.fnal.gov/cgibin/ShowDocument?docid=1059